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Original Articles

Phytoplankton production in relation to simulated hydro- and thermodynamics during a hydrological wet year – Goczałkowice reservoir (Poland) case study

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ABSTRACT

Phytoplankton is one of the crucial components of water body ecosystems. Its presence and development depend on biological, physical and chemical factors and in consequence it is an important indicator of ecosystem condition. Monitoring of phytoplankton production, measured as chlorophyll *a* concentration, is a useful tool for assessing the status of dam reservoirs. Modeled chlorophyll *a* concentrations are used as water quality indicators in locations not included in monitoring systems, in situations when the temporal resolution of the monitoring is not enough, and in assessments of the impacts of future activities. Therefore, the aim of this study was to find correlations between hydro- and thermodynamics and the chlorophyll *a* concentration for possible application in reservoir monitoring and management, using an ELCOM-CAEDYM model. The analysis included summer and fall which are most prone to algal blooms, and four phytoplankton groups identified as dominant in the reservoir based on periodic observations.

Comparisons of simulated water temperature and both observed and simulated chlorophyll *a* concentrations confirmed that these variables are significantly correlated (correlation of hourly chlorophyll *a* and water temperature was 0.70, ranging from 0.55 to 0.81 in the bottom and surface water layers, respectively, while for daily outputs it was 0.74, ranging from 0.60 to 0.83). This relation was stronger than that of chlorophyll *a* to nutrient (N, P and Si) concentrations. What is more, the method used allowed the assessment of a much more detailed spatial and temporal distribution of phytoplankton groups compared with conventional monitoring techniques.

The study indicated that the phytoplankton community was dominated by Chlorophytes and Diatoms with a larger share of Chlorophytes in shallow parts of the reservoir. This domination was weaker after short water mixing events in summer and especially after the fall turnover. The increase in phytoplankton diversity was estimated to occur mainly near the surface and in shallow parts of the reservoir. Most of the observed concentrations of individual phytoplankton groups differed from simulation results by less than 25% and the model reflected accurately 74% of observed trends in concentrations. Calculated chlorophyll *a* concentration was well matched to hourly monitoring data (mean squared error = 5.6, Nash–Sutcliffe model efficiency coefficient = 0.51, Pearson correlation coefficient = 0.72 and p-value = 0.0007).

High compatibility of the model to the values measured in the reservoir make it a promising tool for the prediction and planning of actions aimed at maintaining good functioning of the reservoir.

1. Introduction

Phytoplankton is one of the key components of aquatic ecosystems. Changes in phytoplankton abundance affect other trophic levels, stimulating or limiting the biological diversity (French and Petticrew, 2007; Hambrook Berkman and Canova, 2007). Moreover, excessive phytoplankton growth can have a detrimental effect on water treatment processes, posing a risk to drinking water supplies (French and

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Petticrew, 2007; Graham et al., 2008). This negative effect may result from increased turbidity, toxins produced by some organisms (e.g. cyanobacteria), increased concentrations of trihalomethane (THM) precursors, or the taste and odor caused by certain algal species (Graham et al., 2008; Hambrook Berkman and Canova, 2007).

Changes in phytoplankton production in lakes and reservoirs are reflected by increased chlorophyll *a* concentrations and may have different patterns depending on geographic region and more specifically on the climate, lake bathymetry, morphology and land use of the basin affecting inflows to the lake (French and Petticrew, 2007). Water temperature and hydrology strongly affect phytoplankton dynamics (Elliott, 2010; Rangel et al., 2012). The temperature in lakes and reservoirs decreases with depth as a result of light intensity. In lakes and rivers, two zones can be identified: photic (called also euphotic) and aphotic. The first one is the surface water layer, where there is enough light to support photosynthesis (Graham et al., 2008). The surface layer is also favorable for phytoplankton growth because of its higher temperature, increasing the growth rate (Graham et al., 2008) and sometimes decreasing the zooplankton grazing rate (French and Petticrew, 2007).

Phytoplankton biomass is the key parameter reflecting the ecological effect of eutrophication in lakes and reservoirs (Wang et al., 2013). Therefore, monitoring, simulation and forecasting of chlorophyll *a* concentration is of great importance in anthropogenically affected areas, in protected areas and in reservoirs serving for drinking water supplies or recreation, especially currently, when changes effected by global warming have resulted in water scarcity in many regions of the world (https://www.unwater.org/water-facts/climate-change/). Several methods of measuring chlorophyll *a* concentration are widely used, starting from basic sampling methods and laboratory analysis (e.g. extraction and fluorometric/spectrometric/chromatographic detection), through automatic sensors (fluorescence-based sensors) and finishing with remote sensing techniques (analyses of multi- or hyper-spectral satellite and aircraft observations) (Cannizzaro and Carder, 2006; Hambrook Berkman and Canova, 2007; Hedger et al., 2002; Zhang et al., 2011). All of these methods provide information on the water quality status which can be used directly to support water management and decision-making processes or can be used to support simulations and forecasting of changes in water ecosystems. The latter application of water quality monitoring data is possible thanks to the mathematical modeling which dates back to the 1970s (Vollenweider, 1975). These models include simple regression models, multiple regression models, autoregressive moving average models, artificial neural networks and process-based models (Wang et al., 2013).

This paper presents an application of a three-dimensional (3D) Computational Aquatic Ecosystem DYnamics Model (CAEDYM) to simulate phytoplankton dynamics in a shallow dam reservoir (Goczałkowice Reservoir) in Southern Poland (Silesia region). Application of this model will support management of the water quality in the reservoir. This approach is recommended for monitoring water pollution and quality status (e.g. USEPA, 2015). The support for reservoir management is here considered as the provision of information on the effects of, e.g. (1) changing weather conditions (the model presented was operating in real-time mode), (2) climate change scenarios and (3) modification of the reservoir's bathymetry (for example by dredging). The effect in terms of phytoplankton abundance is an important factor in decisions on the operation of intakes located in the reservoir. The aim of the research was to find relations between hydro- and thermodynamics and the chlorophyll *a* concentration describing changes of phytoplankton production, to potentially apply it as an early warning system, as well as for prediction and planning of protective actions. The model was established as a result of the "Integrated system supporting management and protection of water reservoir" (ZiZOZap) project conducted on the basis of the Goczałkowice Dam Reservoir (Silesia region).

In addition to the application of mathematical modeling, the study included collection of available monitoring data and implementation of detailed research monitoring (comprising real-time meteorological and water quality measurements). These data are the exemplification of the phenomena taking place in the reservoir in a hydrological wet year.

Goczałkowice Reservoir is the biggest dam reservoir in the south of Poland – Silesia region. It covers over 32 km^2 and has two main inflows: the Small Vistula River (the main inflow, approx. 80%) and the Bajerka River. The reservoir has a bottom outflow at the reservoir front dam (latitude: 49.932689 °N; longitude: 18.929941 °E). The total basin area is 530 km^2 (Fig. 1).

The reservoir was created in 1955 and it serves as a main part of the system supplying the Upper Silesian agglomeration (approx. 3.4 million inhabitants) with potable water. It is also a storage reservoir, protecting downstream areas from floods and droughts. Additionally, the reservoir, being a part of the Natura 2000 system, helps to protect a wide range of habitats and species (Dabioch et al., 2013; Młynarczyk et al., 2013; Polak et al., 2011). The reservoir is included in the national monitoring system and since 2010 extensive research monitoring has been carried out in the framework of the ZiZOZap project. Both periodic water sampling and real-time measurements indicate strong changes in the water quality, posing a risk to water treatment plants and biodiversity. Taking into account that significant changes in water quality occur in short periods (even in one day), it was assumed that these changes may result to a large extent from thermal- and hydrodynamic conditions rather than the availability of nutrients in inflows. Therefore, the goal of the presented study was to test the hypothesis that changes in phytoplankton production in the analyzed reservoir are driven mainly by water temperature and mixing, and to assess how fluctuations in water temperature and water mixing affect the abundance, composition and spatial distribution of phytoplankton.

2. Methods

2.1. Model setup and assumptions

In the presented research, a coupled Estuary, Lake and Coastal Ocean Model (ELCOM)-CAEDYM model was applied to investigate the relations between hydro- and thermodynamics and phytoplankton dynamics (concentration or development). The main steps in the model application and in the presented study are depicted in Fig. 2.

The key model selection criteria included the following capabilities: simulate water flow, temperature and quality (at least the cycle of sediments, nutrients and phytoplankton) in a set of cells or elements composing the 3D structure of water bodies; simulate long periods (at least several months); time step not larger than 1 h; use hot start files to set initial conditions in a water body based on previous simulation; run in a Linux system as a scheduled task to enable use of the model as a real-time or forecasting tool; and generate outputs in the form of time series that can be visualized in the form of tables, charts, maps and cross-sections. In addition, it was not without relevance that the selected models allow simulation of the impact of meteorological conditions on both the thermodynamics and phytoplankton growth, and that the model can include several phytoplankton groups which can be parameterized in detail regarding their growth limiting factors, respiration, motility, etc. CAEDYM is a process-based aquatic ecological model that can be configured to simulate nitrogen, phosphorus, silica and oxygen cycles, suspended solids and phytoplankton dynamics. CAEDYM optionally can simulate bacteria, macrophytes, zooplankton, fish and benthic invertebrates. The model does not simulate transport of variables; therefore, it has to be coupled with a suitable hydrodynamics model such as 1D DYRESM, quasi 2D DYRIM, 2D DIVAST or 3D ELCOM (Hipsey, 2012; Hipsey et al., 2012). For the Goczałkowice Reservoir, ELCOM was applied as the hydrodynamics driver. ELCOM is a 3D hydrodynamics model for lakes and reservoirs, and is used to simulate the variation of water temperature and salinity in space and time (Hodges and Dallimore, 2013). At present, the model is distributed as Aquatic Ecosystem Model 3D (AEM3D) which is an upgraded version of the ELCOM-CAEDYM software (http://www.hydronumerics.com.au/software/aquatic-ecosystem-model-3d).

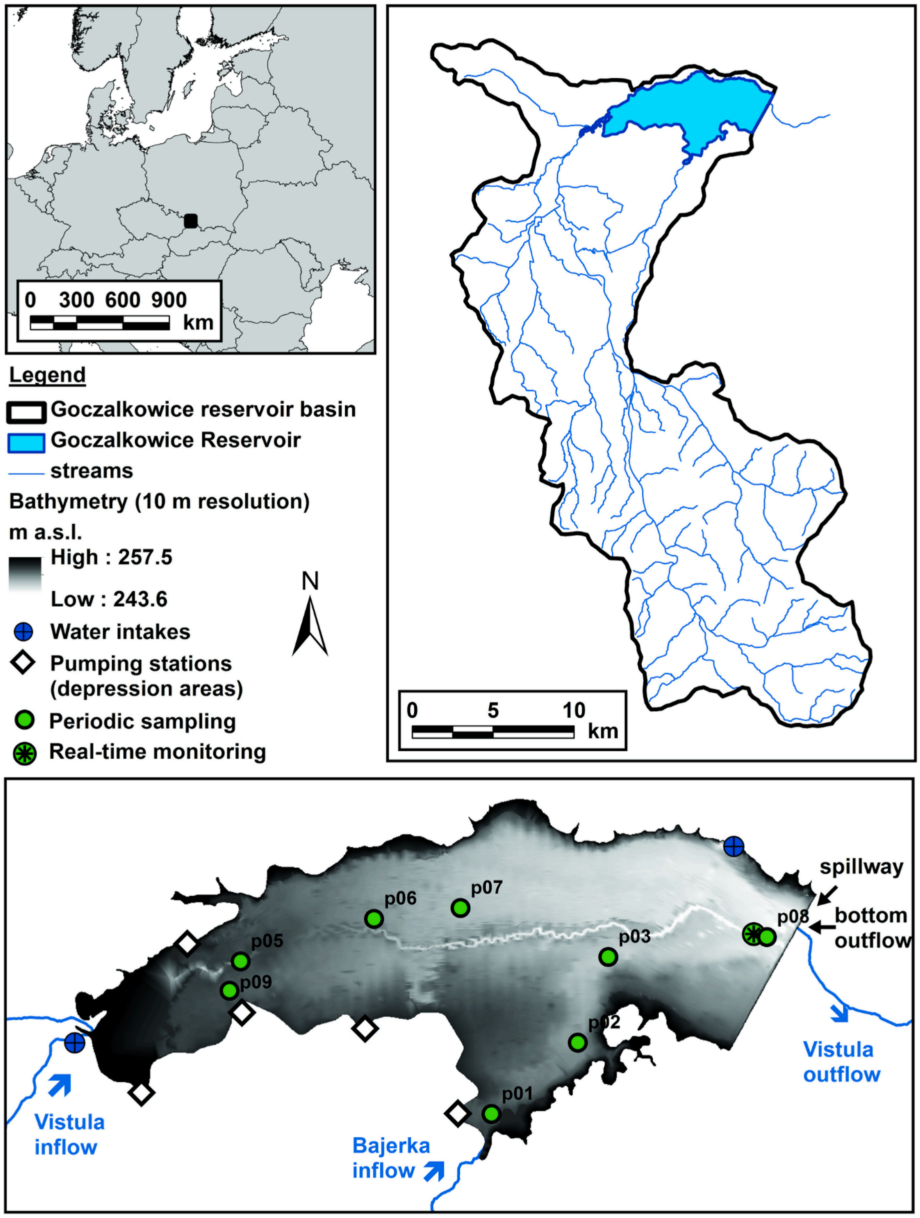

Fig. 1. Localization of Goczałkowice Reservoir in Europe, Goczałkowice Reservoir basin and localization of crucial points on the reservoir.

The model of Goczałkowice Reservoir presented here was applied (tested and calibrated) for a period of 6 months: June to November 2010. The model time step was set to 5 min. The starting time was determined by the setup of a real-time monitoring system which was fully operational in June. The 6-month analysis period was chosen in order to be: 1) long enough to include significant changes in phytoplankton production and 2) as short as possible to enable the multiple iterations required for model calibration in an acceptable time.

The model of Goczałkowice Reservoir consists of 15 layers of thickness varying from 0.5 to 1.25 m. A thickness of 0.5 m was applied to four surface water layers (up from 255.25 m a.s.l.), a thickness of 1.25 m was applied to the bottom layer (244–245.25 m a.s.l.) and a thickness of 1 m was used for the ten intermediate layers. Only 12 of the 15 model layers are usually wet, with the average water table elevation at 255.5 m a.s.l. The next three layers of 0.5 m thickness are reserved for higher water levels, with the maximum impoundment level at 257 m a.s.l. The horizontal resolution of the model is 100 m, resulting in 119 columns, 60 rows and 41,683 total calculation cells. The model includes seven inflows: the Vistula River (the main inflow), the Bajerka River and five pumping stations transferring the excess water from depressed, agricultural and grassland areas around the western part of the reservoir (Fig. 1). The average inflows in the analyzed period are as follows: Vistula 7.98 $m^3\ s^{-1}$, Bajerka 0.40 $m^3\ s^{-1}$ and pumping stations together 0.41 $m^3\ s^{-1}$. Outflows include: intake (average 2.02 $m^3\ s^{-1}$), spillway (average 7.07 $m^3\ s^{-1}$) and bottom outflow required for the protection of ecosystems downstream (0.6 $m^3\ s^{-1}$). The temporal resolution of all inflow and outflow data is 1 day and all inflows include information on the water temperature. The model included inputs from one meteorological station located above the water surface near the Bajerka River inflow. Meteorological data are of hourly resolution. The real-time water monitoring system launched in 2010 included, among other parameters, the water temperature at different water depths and the concentration of chlorophyll *a*. These data together with periodical measurements were used for model calibration and verification.

2.2. Hydrodynamic model driver

As mentioned above, the CAEDYM model requires an external hydrodynamic driver providing information on water velocity, temperature and salinity. In the case of the Goczałkowice Reservoir, the ELCOM

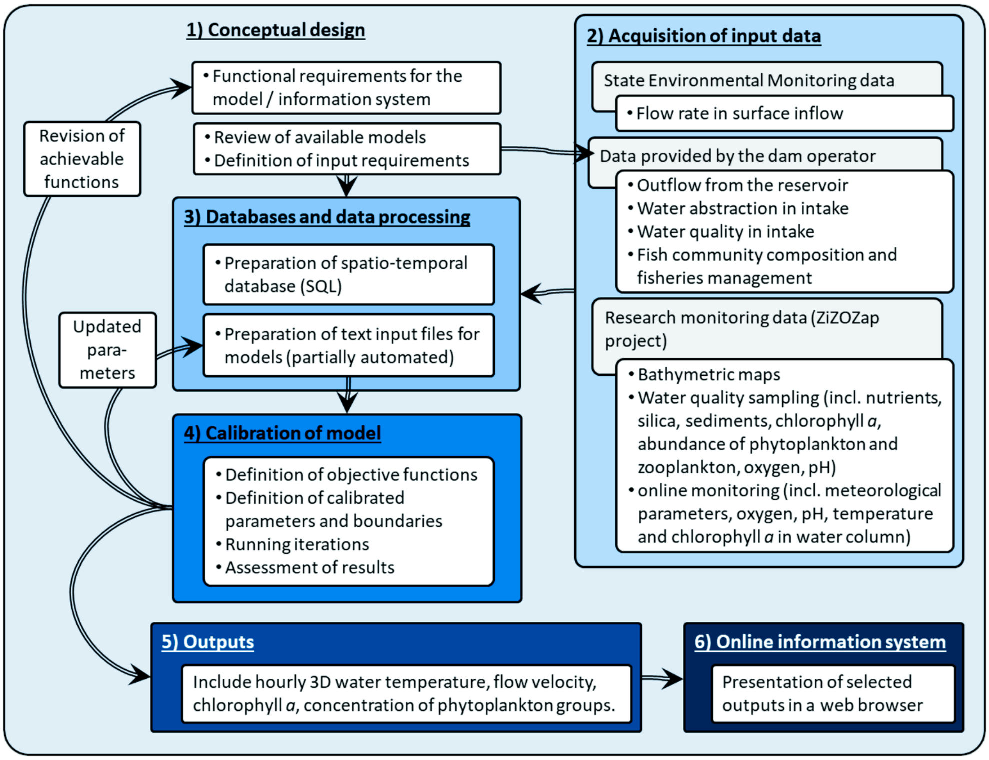

Fig. 2. Flowchart presenting the work process (main steps in the presented study).

model was chosen as this driver. ELCOM and CAEDYM models are coupled in such a way that the CAEDYM subroutine is called at each step of the hydrodynamic model's calculations (Hipsey et al., 2012).

In ELCOM, the heat exchange through the water's surface is governed by standard bulk transfer models. The energy transfer across the free surface is separated into nonpenetrative components of long-wave radiation, sensible heat transfer and evaporative heat loss, complemented by penetrative shortwave radiation. Nonpenetrative effects are introduced as sources of temperature in the surface-mixed layer, whereas penetrative effects are introduced as source terms in one or more grid layers on the basis of an exponential decay and an extinction coefficient (Hodges and Dallimore, 2013).

The 6-month analysis period can be divided into two parts, differing in respect of variations in the temperature in water profiles. The first part started at the beginning of summer (middle of June) and lasted till late summer (end of August). This part can be easily distinguished by larger differences in surface and bottom water temperatures (the average difference is 3.3 °C and the maximum is 10 °C) and by short water mixing events. The second period, considered as autumn, started at the beginning of September when the last water mixing event occurred and was not followed by any significant thermal stratification. In this period, water was well mixed and variations in the water temperature were less than 2 °C (Ulańczyk et al., 2018).

From an ecological point of view, the first period (summer) was crucial as it included several events of increased chlorophyll *a* concentration (50 μg L^{-1} observed at the real-time monitoring point in the center of lake). As increased algal growth is often preceded by water mixing events (Boehrer and Schultze, 2008), Section 3 is dedicated to the interactions between lake hydrodynamics (or thermodynamics) and changes in phytoplankton dynamics. An example of the simulated distribution of water temperature and flow velocity during a summer water mixing event is presented in Fig. 3.

2.3. Parameterization of the ecological model

The CAEDYM model prepared for Goczałkowice Reservoir included four groups of phytoplankton, two groups of zooplankton and three groups of fish (see details in Table 1). The model also included simulations of 1) bacterial biomass, 2) cycling of standard chemical compounds: nitrogen, phosphorus, silica and carbon, and 3) two inorganic particle groups. Settling and resuspension of both organic and inorganic components was taken into account, together with the adsorption and desorption on inorganic particles.

Phytoplankton biomass in the model is represented by chlorophyll *a* and its dynamics include six main processes: growth, mortality, respiration, excretion, grazing by zooplankton and vertical migration. Algal growth is limited by light, nutrient (N and P) availability, silica availability in the case of diatoms, and temperature. The growth rate for all phytoplankton groups is calculated using the same method with three exceptions. The first one is the silica uptake assigned to Diatoms only; the second is the nitrogen fixation ability of Cyanobacteria; and the third is the light limitation function which has a simplified form for all groups except Flagellum-possessing species. This simplified function ignores the light saturation value at which algal production is maximal. In the Goczałkowice Reservoir model of phytoplankton, groups are distinguished also by three migration algorithms: 1) the first based on a constant settling velocity assigned to the Diatom group, 2) the second, a migration algorithm without photoinhibition, assigned to Cyanobacterium and Chlorophyte groups and 3) the third, a migration algorithm with photoinhibition assigned to the Flagellum-possessing species.

3. Results

In the 6-month analysis period (summer and autumn 2010), several peaks in chlorophyll *a* concentration occurred (Fig. 4). All of the significant ones were observed in summer, reaching as high as 90 μg L^{-1}, while the average chlorophyll *a* concentration was ten times less.

Of the 650 CAEDYM model iterations, the best simulation was chosen based on matching observed vs calculated concentrations of chlorophyll *a*. Chlorophyll *a* is the phytoplankton dynamics indicator which was easiest to monitor in real time and at high temporal resolution (hourly measurements). The model calibration included 87 parameters

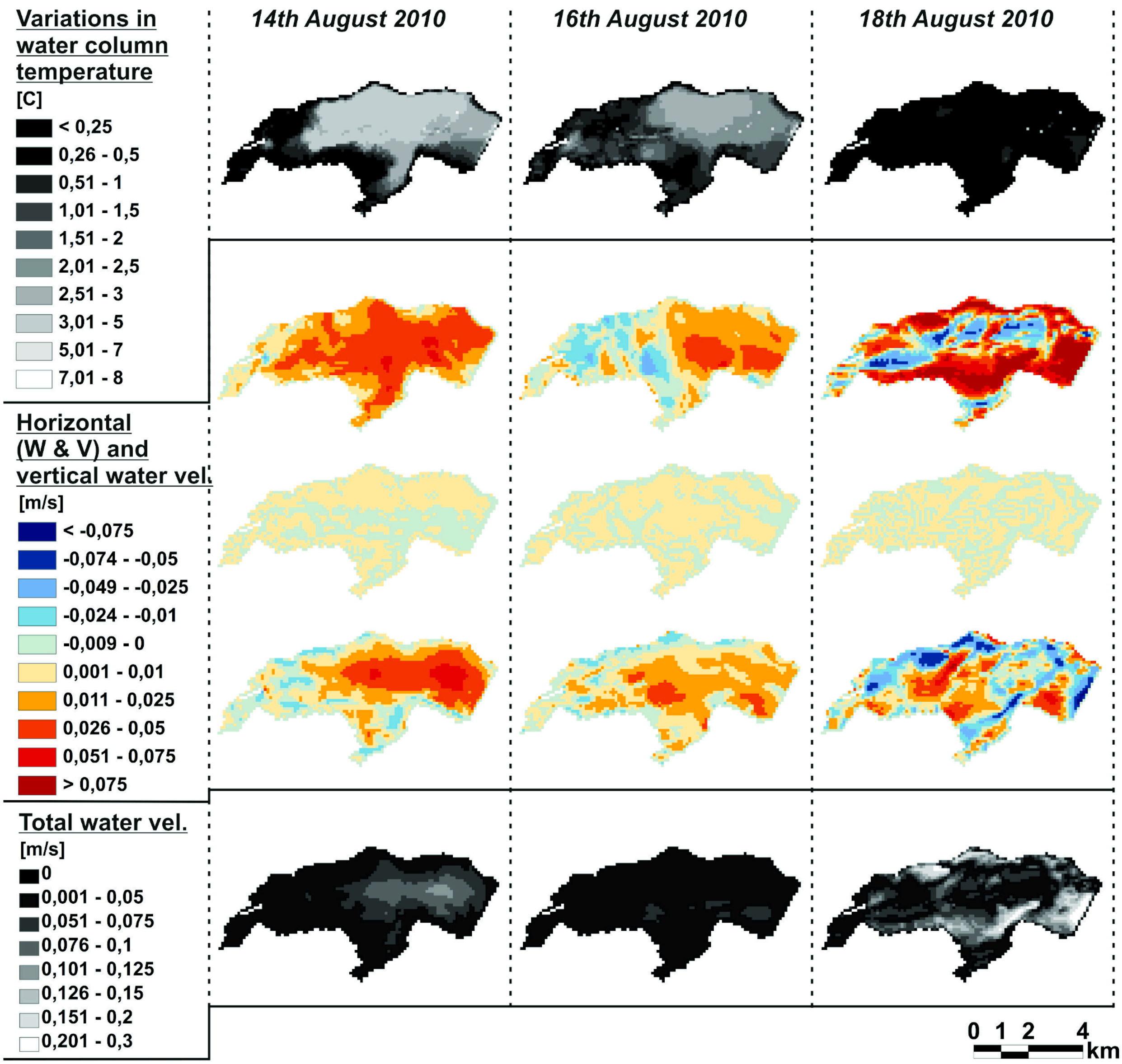

Fig. 3. Example of simulated water temperature (upper part of the figure) and velocity during a water mixing event between 14th and 18th August 2020. The first column presents the status before the mixing event and the last column presents the result of the event.

(Table 2) and over 3000 hourly observed chlorophyll *a* concentrations. The choice of the best simulation was based on three statistical parameters: mean squared error (MSE), Nash–Sutcliffe (NS) model efficiency coefficient (Nash and Sutcliffe, 1970) and Pearson correlation coefficient (R). The best simulation (Fig. 5) confirms the model accuracy, with MSE = 5.6, NS = 0.51, $R = 0.72$ and $p = 0.0007$).

After calibration of the model, it was used to simulate phytoplankton production dynamics in terms of chlorophyll *a* concentration. Both spatial and temporal changes in chlorophyll *a* concentrations were of significant magnitude (Fig. 6), reaching 100 μg L^{-1}. Such changes are observed 1) in vertical water profiles in summer when the top water layer is rich in plankton, 2) across each water layer and especially in the bottom layer in summer, with the highest chlorophyll *a* concentrations in the shallow areas near banks and in the backflow area to the west of the Vistula River inflow and 3) in time due to the water mixing events described below.

As previously specified, there are four groups of phytoplankton in the model of Goczałkowice Reservoir. According to features of these groups, they were called: Flagellum-possessing species (FLAGE), Cyanobacteria (CYANO), Chlorophytes (CHLOR) and Diatoms (DIAT). In addition to the comparison of modeled and observed concentrations of chlorophyll *a* as a whole described above, each group of phytoplankton was analyzed separately. To enable such analyses, the total mass of phytoplankton had to be measured and divided into the four modeled groups based on the species identified in water samples. The phytoplankton monitoring campaign was carried out in 2010–2012 and included 87 water samples picked from eight monitoring points (Fig. 1). Based on such measurements, 29 species of phytoplankton were assigned to the FLAGE group in the Goczałkowice Reservoir, the dominant of which were *Phacus longicauda* (21.70% of FLAGE mass), *Ceratium hirundinella* (15.20%), *Cryptomonas* sp. (12.27%) and *Trachelomonas volvocina* (10.29%). The CYANO group includes 21 species of phytoplankton, e.g. *Phormidium* sp. (32.11% of CYANO mass), *Microcystis aeruginosa* (19.24%), *Aphanocapsa* sp. (18.75%) and *Snowella litoralis* (14.08%). The CHLOR group includes 62 species, e.g. *Dictyosphaerium pulchellum* (18.44% mass of CHLOR), *Pediastrum simplex* (15.35%), *Pediastrum boryanum* (10.86%) and *Botryococcus braunii* (8.88%). The last group (DIAT) includes 39 species, mainly *Aulacoseira granulata* var. *angustissima* f. *curvata* (21.99% mass of the group), *Melosira varians* (20.33%), *Cyclotella meneghiniana* (17.10%) and *Navicula cuspidata* (14.99%).

Table 1
Plankton and fish groups included in the CAEDYM model for Goczałkowice Reservoir.

Group name/ identification	Description
Phytoplankton	
Flagellum-possessing species	Group represents a type of mixotrophic organism. The main feature of species included in the group is the ability to rotate through the water using flagella (motility). High abundance of those species may indicate high bacteria consumption since those species may also use bacteria as a source of nutrients.
Cyanobacteria	Cyanobacteria are colonial bacteria with a prokaryotic cell structure; however, cyanobacteria also have chlorophyll *a* characteristic of eukaryotic algae and higher plants (Graham et al., 2008; Reynolds, 2006). Because of this photosynthetic functionality, cyanobacteria typically are sampled and analyzed as part of phytoplankton (algal) assemblages rather than bacterial assemblages in aquatic ecosystems (Graham et al., 2008). The features of this group reflected in the CAEDYM model are buoyancy control and nitrogen fixation and uptake (Hipsey et al., 2012).
Chlorophytes	Green-pigmented, unicellular, colonial, filamentous, siphonaceous and thalloid algae (Reynolds, 2006).
Diatoms	Diatoms (Bacillariophyta) are silica-dependent. Diatoms are unicellular or colonial.
Zooplankton	
Zooplankton 1	A predator group grazing on filter-feeding zooplankton, on zooplanktonic predators themselves and on cyanobacteria.
Zooplankton 2	Filter-feeding zooplankton group grazing on all four groups of phytoplankton, bacteria and detritus, with preference for chlorophytes and diatoms.
Fish	
Fish 1	A group of small fish of mixed species and length less than 5 cm. This group feeds on phytoplankton, zooplankton, detritus and small fish, with a preference for diatoms.
Fish 2	Medium-sized fish of mixed species and length between 5 and 15 cm. Grazing on phytoplankton, zooplankton, detritus, and small and medium fish. The most preferred sources of nutrients for this group are diatoms and small fish.
Fish 3	Group of large fish of length more than 15 cm grazing mostly on fish. Detritus and plankton also provide this group with nutrients but they are of minor importance.

In the analyzed period (summer–autumn 2010), comparison of simulated and observed abundance of the four phytoplankton groups was limited to six out of eight monitoring points and included samples picked twice: on the 16th August and 14th September 2010. Simulated abundance of each phytoplankton group is presented in Figs. 7 and 8 in the form of distribution maps for selected dates (one for stratified and one for mixed water conditions) and in the form of graphs prepared for monitoring point locations.

The overall model verification in terms of matching observed concentrations of chlorophyll *a* for each group of phytoplankton was satisfactory (Fig. 9). Figures which illustrate that are: (1) 57% of simulated concentrations had an error lower than 25%, (2) the error for all summer samples was lower than 25%, (3) one-third of samples were fully matched with simulated concentrations (meaning that the range of simulated concentration for the monitored day 6:00 AM–6:00 PM and location included the observed value) and (4) 74% of observed trends in concentrations were reflected by the model (88% when FLAGE is excluded).

During the whole phytoplankton monitoring campaign consisting of 87 samples, it was assessed that the Flagellum-possessing species group is 8.71% of the total phytoplankton mass in the reservoir, the

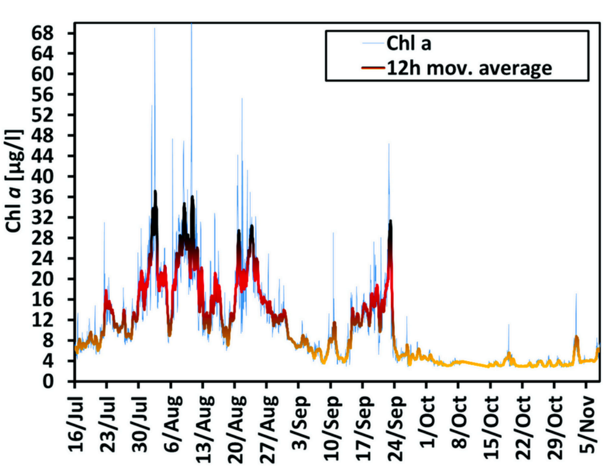

Fig. 4. Observed chlorophyll *a* concentrations in the Goczałkowice Reservoir in 2010: thin line is hourly observations and thick gradient line is 12 h (period) moving average.

Cyanobacteria group is 23.96%, the Chlorophytes group is 25.23% and the Diatoms group is 38.61%. These numbers are in accordance with the CAEDYM model outputs regarding the domination of phytoplankton groups in the Goczałkowice Reservoir. The model indicated that the dominant group is the Diatoms group with 37% of total phytoplankton mass; next are Chlorophytes and Cyanobacteria in the same order as observed and with 34% and 19% of total mass; finally, Flagellum-possessing species in the model constitute the smallest group with 9% of the total phytoplankton mass. However, along with changes of phytoplankton concentrations in time and in space (Figs. 7 and 8), the percentage share of different groups changed as well (Fig. 10).

Both the periodical monitoring and the model indicate that the highest concentration of algae can be found near inflows and in shallow parts of the reservoir. The concentration decreases significantly in the deeper part. In the shallow part, there is a clear alteration in phytoplankton communities. In summer, the Chlorophytes group is dominant, exceeding 80% of total phytoplankton mass. After destratification, however, Chlorophytes constitute the smallest of the four analyzed phytoplankton groups (Fig. 10). In the deeper part of the reservoir, the share of phytoplankton groups in the total mass is more constant, with Diatoms and Chlorophytes as the dominant groups.

During the summer, three water mixing events occurred in the reservoir, lasting 4–5 days. Before these events, the average difference between bottom and surface water temperature was 4–10 °C. After mixing events, the water temperature difference decreased to 0–1.5 °C. At the end of the summer, there was a final water mixing event, which resulted in uniform temperature in water profiles and then the reservoir remained destratified (an example of such an event is presented in Fig. 11). Chlorophyll *a* concentration increased from 7 to 70 µg L^{-1}, from 7 to 90 µg L^{-1} and from 7 to 55 µg L^{-1} for the three events mentioned above.

Thanks to the simulation of phytoplankton growth, it was possible to analyze the correlations between simulated water temperature, flow velocity and chlorophyll *a*. It was estimated that the correlation for hourly outputs regarding chlorophyll *a* and water temperature was 0.70, ranging from 0.55 in bottom water layers (1 m) to 0.81 in top water layers (1 m). In the case of daily changes in temperature and chlorophyll *a*, the correlation was 0.74, ranging from 0.60 in bottom water layers to 0.83 in top water layers. In the case of individual groups of phytoplankton, the average correlation varied from 0.14 to 0.72. And finally, when depth-averaged temperatures and chlorophyll *a* concentrations were considered, the correlation was 0.88. All correlations mentioned

Table 2
Calibrated parameters in the CAEDYM model (calibration boundary values in brackets).

Phytoplankton parameters		Flagellum-possessing species	Cyanobacteria	Chlorophytes	Diatoms
Respiration rate coefficient		0.2 (0.07–0.2)	0.2 (0–0.26)	0.112 (0–0.2)	0.095 (0–0.2)
Light saturation for maximum production (μEm^2 s^{-1})			500 (500–1300)	300 (100–300)	100 (70–200)
Initial slope of photosynthesis-irradiance curve (μEm^2 s^{-1})		140 (30–140)	50 (50–150)	100 (40–100)	80 (40–80)
Maximum potential growth rate (day^{-1})		0.3 (0.3–1.5)	0.6 (0.35–1.1)	1.5 (0.4–1.9)	2.4 (0.47–2.8)
Temperature for growth (°C)	Optimum	20 (20–22)	28 (20–30)	24 (22–31.5)	18 (18–25)
	Maximum		35 (35–39)	30 (30–40)	30 (30–31)
	Standard	20	24 (20–24)	17 (17–24)	15 (15–24)
Half saturation constant for P		0.00083 (0.00083–0.001)	0.001 (0.001–0.006)	0.001 (0.001–0.002)	0.001 (0.001–0.004)
Maximum/minimum internal N concentration (mg N mg Chl*a*$^{-1}$)			10 (5–10)/4.24 (2.5–4.24)		
Maximum/minimum internal P concentration (mg P mg Chl*a*$^{-1}$)			1.44 (1–1.5)/ 0.14 (0.1–0.3)		
Average ratio of carbon to chlorophyll *a*			50 (40–50)		
Sediment survival time (days)			1 (1–100)		
Specific attenuation coefficient (μg Chl*a* L^{-1} m^{-1})		0.05 (0.0067–0.05)	0.1 (0.014–0.1)	0.06 (0.014–0.06)	0.06 (0.014–0.06)
Minimum density (kg m^{-3})			980 (980–990)		
Temperature multiplier for respiration			1.08 (1.03–1.14)		1.07 (1.03–1.2)

Zooplankton parameters		Group 1	Group 2
Respiration rate coefficient		0.06 (0.06–0.3)	0.06 (0.06–0.3)
Temperature for growth (°C)	Optimum	13 (13–21)	
	Standard	13 (13–16)	
	Maximum	33 (33–36)	
Zooplankton grazing preference	Detritus	0 (0–0.3)	0.2 (0.18–0.2)
	Flagellum-possessing species	0.01	0.01 (0–0.1)
	Cyanobacteria	0	(0.01–0.05)
	Chlorophytes	0.01	0.4
	Diatoms	0.01	0.2
	Zooplankton group 2	0.6 (0.5–0.6)	
Grazing rate of zooplankton on phytoplankton ((g phyto C m^{-3}) (g zoo C m^{-3})$^{-1}$ day^{-1})		2.1 (0.7–2.1)	2.8 (0.5–2.8)

Fish parameters		Group 1	Group 2	Group 3
Respiration rate coefficient		0.028 (0.015–0.03)	0.024 (0.01–0.025)	0.012 (0.007–0.02)
Grazing rate ((g food C m^{-3}) (g fish C m^{-3})$^{-1}$ day^{-1})		0.42 (0.25–0.45)	0.4 (0.20–0.4)	0.38 (0.15–0.5)
Minimum dissolved oxygen tolerance for fish (mg L^{-1})		4 (3.5–4)	4 (3.5–4)	4 (3.5–4)
Half saturation constant for DO dependence for fish (mg L^{-1})		4 (3.5–4)	4 (3.5–4)	4 (3.5–4)
Fish preference	Flagellum-possessing species	0.1 (0–0.1)		
	Cyanobacteria	0 (0–0.1)		
	Chlorophytes	0.1 (0–0.1)		
	Diatoms	0.1 (0–0.1)		

Bacteria parameters	
Respiration rate constant for bacteria in water column	0.6 (0.5–0.6)
Bacterial OM consumption preferences for POM (decimal %)	1 (0.2–1)
Bacterial OM consumption preferences for DOM (decimal %)	1 (0.15–1)
Bacterial excretion of DOC in sediments (day^{-1})	0 (0–0.7)
Half saturation constant for bacteria function in sediments (day^{-1})	0 (0–0.5)
Half saturation constant for bacteria function in water column (day^{-1})	0.01 (0.01–0.5)
Half saturation constant for bacteria, for DO dependence of POM/DOM decomposition (mg L^{-1})	1.5 (1.5–3)
Chemical parameters	
Maximum transfer of POCL → DOCL in POM (day^{-1})	0.01 (0.01–0.005)
Maximum transfer of PONL → DONL in POM (day^{-1})	0.005 (0.002–0.005)
Maximum transfer of POPL → DOPL in POM (day^{-1})	0.01 (0.01–0.005)
Maximum mineralization of DOCL → DIC in DOM (day^{-1})	0.012 (0.003–0.1)
Nitrification rate coefficient in dissolved inorganics (day^{-1})	0.05 (0.01–0.05)
Maximum mineralization of DONL → NH_4 in DOM (day^{-1})	0.01 (0.01–0.05)
Half saturation constant for DO sediment flux (mg O L^{-1})	4 (0.4–4)

above can be considered as significant, with a p-value much lower than 0.1% (in most cases equal to 0). Only for Flagellum-possessing species was the p-value greater (1.18%).

For all the correlations mentioned above, the relation of chlorophyll *a* to water temperature is stronger than the relation of chlorophyll *a* to the concentration of nutrients (N, P and Si). Similar analyses were made for a horizontal component of flow velocity and for the chlorophyll *a* concentration. In that case, the correlation of daily outputs ranged from 0.66 near the bottom to −0.29 near the water surface. However, the correlation of changes in the vertical flow velocity and changes in the chlorophyll *a* concentration is of greater importance, because it indicates the impact of vertical flow (mixing of water layers) on the change in chlorophyll *a* concentration (an increase is expected here). Indeed, such correlation for 3-day changes was equal to 0.81, ranging from 0.66 to 0.89 in individual water layers (p-value <0.001).

4. Discussion

The research hypothesis of the study was that changes in phytoplankton production in the reservoir are driven mainly by water temperature and mixing. These two factors together with simulated chlorophyll *a* concentration were presumed to be indicators of great importance in planning activities related to reservoir management and in forecasting rapid changes in the water quality (considered as a risk for water intakes). To verify this hypothesis and to assess if the verification was based on a properly designed work process and results, three aspects of this study are discussed below. The first may be considered as an approach – tools, methods and a general work flow; the second focuses

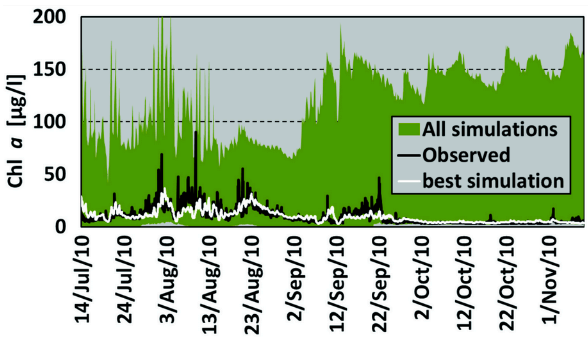

Fig. 5. Comparison of observed and simulated chlorophyll *a* concentrations in the Goczałkowice Reservoir in 2010 (green area represents the maximum and minimum concentrations calculated with all iterations of the model calibration).

on the processes simulated in the study and the importance of taking into consideration complex interactions of the factors affecting water quality; and the third is the achieved outcome of the study, i.e. the usefulness of the results and applicability and transferability of the tools developed.

4.1. Approach to the simulation of phytoplankton production

The quantity and quality (i.e. assemblages of species) of phytoplankton are among the most important ecological indicators of the equilibrium of an aquatic ecosystem. The application of models, using various traits connected to or describing phytoplankton, such as chlorophyll *a* concentration, appear useful not only for current monitoring of ecosystem status but also prediction of possible changes following changes in related parameters (Derot et al., 2020). This indicator is the subject of modeling studies on a local scale (Absalon et al., 2020) but is also an indicator contributing to global policymaking, e.g. to assessment of the achievement of the United Nations' Sustainable Development Goal (SDG 6: clean water and sanitation) (Janssen et al., 2019).

The model used in the presented study is a physical-based model, which includes mathematical formulas representing physical, chemical and biological processes related to and driving the production of phytoplankton. On one hand, this type of model can be considered as having a solid basis to depict the part of the reality which is the aquatic ecosystem, and on the other hand, statistical models (e.g. Malek et al., 2011; Mamun et al., 2019) are also used commonly and with similar accuracy.

In particular, the attitude utilizing capabilities of modeling tools are crucial for managing multifunctional artificial lakes such as dam reservoirs. Knowledge of the correlation of phytoplankton production with the sources of its variability is helpful in predicting the ecological status of such reservoirs since, as an anthropogenic construction, the distribution of nutrients is determined to some extent by the hydrotechnical elements of the reservoir (Rodrigues et al., 2018). Moreover, the significant correlations between external factors and phytoplankton production enable us to use them as complementary indicators of ecosystem status, which makes immediate protective actions and future scenario analyses possible. Similar analysis of the applicability of the DYRESM-CAEDYM model for indication and monitoring was presented by Cui et al. (2016).

4.2. Simulated processes and results

The main factors with a direct impact on phytoplankton growth within a water body are the availability of nutrients and the water temperature (French and Petticrew, 2007; Hambrook Berkman and Canova, 2007). Liu et al. (2020) analyzed this influence in detail, using numerical tools, in relation to various parameters of phytoplankton production such as subsurface chlorophyll *a* maximum (SCM) depth, thickness and magnitude. The revealed complexity of the phenomenon includes the influence of nutrient content and mixed layer depth on various aspects of chlorophyll *a* concentration (Liu et al., 2020). Together with changes in water temperature (e.g. during thermal stratification or heavy rainfalls, as the result of rainwater inflow, or in the case of flood), the water density changes as well, causing chemical (e.g. nutrient) gradients (Graham et al., 2008). Thermal and chemical stratification may be of seasonal or diurnal character and water mixing processes occur when the solar radiation energy is predominated by winds, currents and other factors causing vertical water flows (Boehrer and Schultze, 2008; Branco and Torgersen, 2009). During more intensive water mixing, substances accumulated in deep (hypolimnetic) water become available near the surface, leading often to increased algal growth and blooms (Boehrer and Schultze, 2008; Yu et al., 2010) – this is also reflected in both observed and simulated concentrations of phytoplankton in the analyzed reservoir. In the present study, nutrient level appeared less significant than water temperature. Such an observation

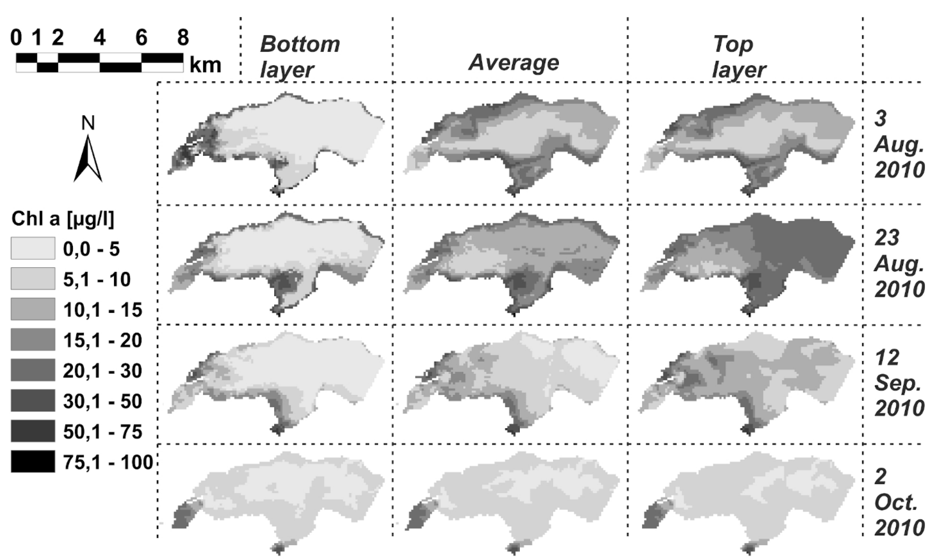

Fig. 6. Simulated chlorophyll *a* concentrations at the bottom, on the surface and in the vertically averaged water layer in the Goczałkowice Reservoir on four summer and fall days.

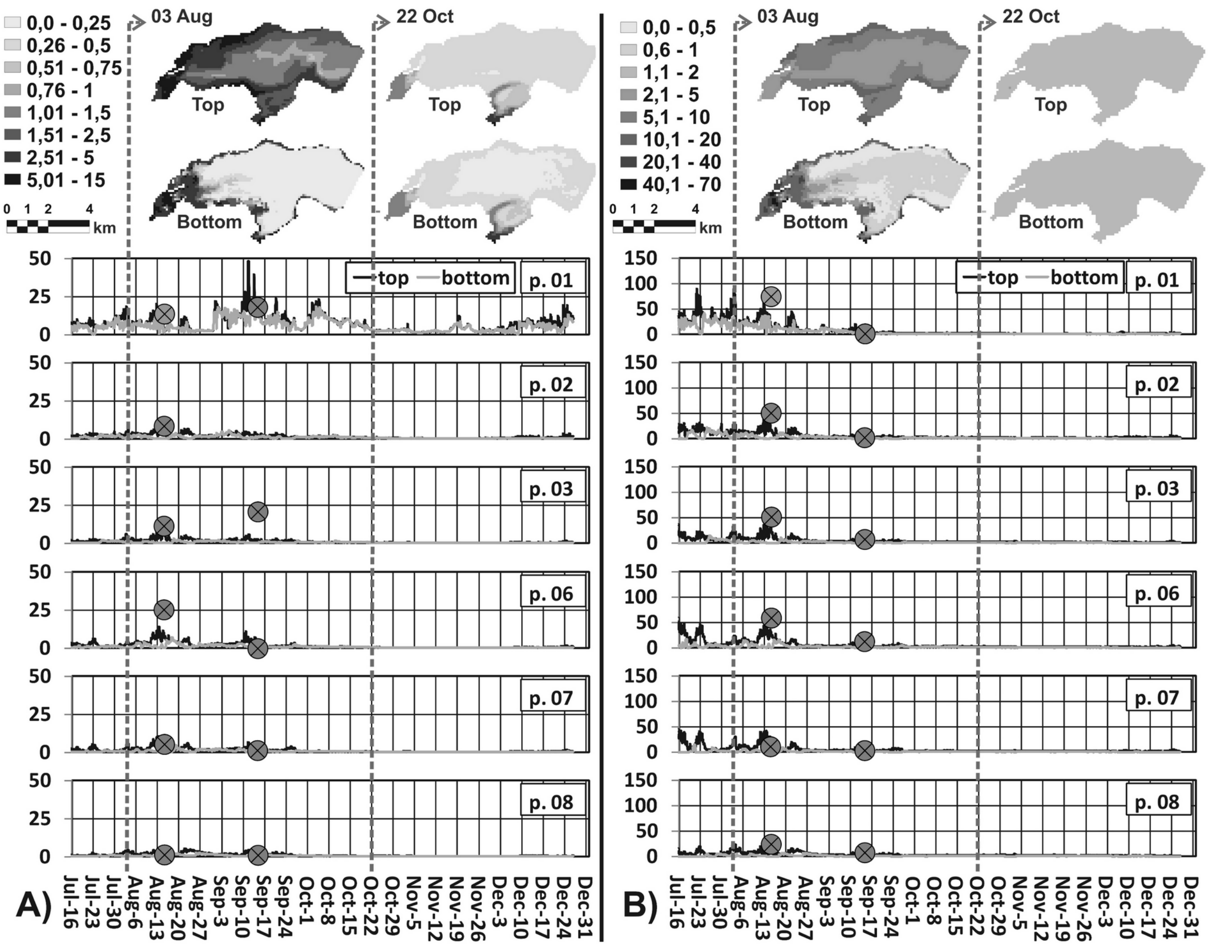

Fig. 7. Simulated changes in the abundance of CYANO (A) and CHLOR (B) phytoplankton groups at monitoring points (for point locations see Fig. 1) and spatial distribution of these groups on 3rd August and 22nd September 2010 (cross-marks represent observed data; dashed vertical lines represent two dates presented on the maps above line charts).

was also made by Belokda et al. (2020) who found no significant correlation between nutrient level and phytoplankton growth. The changes in phytoplankton production in the analyzed reservoir are driven mainly by the water temperature and indirectly by water mixing. This is not a unique feature of Goczałkowice Reservoir, as temperature is reported to be the key factor affecting instantaneous chlorophyll *a* concentration in many other geographical regions (French and Petticrew, 2007; Li et al., 2017).

Nonetheless, it is worth mentioning that the priority of factors influencing the change in phytoplankton production is not only site-specific (characterizing a specific reservoir, lake or group of them), but may have a seasonal pattern or be event-specific, where events are understood as, e.g. floods, droughts, planting/fertilizing or heavy rains. In various periods, the limiting effect of water temperature and nutrient or light availability may differ and be considered (sometimes wrongly) as the most important. For example, when the meteorological conditions are relatively constant in a period of increased load of nutrients entering the reservoir, nutrient availability will be linked to changes in primary production, even though the same nutrient loads in other meteorological conditions could result in minor changes in the chlorophyll *a* concentration. An example of such a diversified impact of temperature and nutrients was reported by Li et al. (2020), who indicated that in one of the two lakes they analyzed, the correlation between temperature and phytoplankton biomass was larger than the correlation between nutrient concentration and phytoplankton biomass. The correlation ranged from 0.19 to 0.61, but in contrast to that for Goczałkowice Reservoir it was not statistically significant. Phytoplankton growth and the related risk of algal blooms (the key concern of the presented study) is a complex process in which a series of factors may play a significant role. Some of these factors are often omitted in analyses, being treated as insignificant or being simply unknown to the analyst/modeler. These factors may include water transparency, changes in the population grazing on the phytoplankton, accidental or unauthorized inputs of pollutants, etc. (Beck, 1987; Guzman et al., 2015; Tscheikner-Gratl et al., 2019). In order to prepare a basis for more complex analyses (such as the one presented in this paper), often there are attempts to analyze individual or limited factors influencing the process of concern. In the case of temperature–chlorophyll *a* and nutrient–chlorophyll *a* dependences, such analyses were presented by Elliott et al. (2006).

The significant relation of the water temperature and chlorophyll *a* concentration in the analyzed reservoir might be a result of specific environmental factors in 2010. During this year, few floods happened. It is obvious that during a flood, the water temperature in the reservoir rapidly changes (decreases), affecting phytoplankton and all communities (Godlewska et al., 2003). These relationships were confirmed by Beaver et al. (2013) who analyzed the effects of drought and intense flood conditions on phyto- and zooplankton in several reservoirs. After a flood, the phytoplankton biovolume values tended to decrease. They also found that physical parameters (including temperature) explain more variance in planktonic structure than nutrient availability (Beaver et al., 2013). Comparisons of simulated water temperature and both observed and simulated chlorophyll *a* concentration in Goczałkowice Reservoir confirm that these two variables are significantly correlated and that the correlation is not exclusive to the surface water layers (a

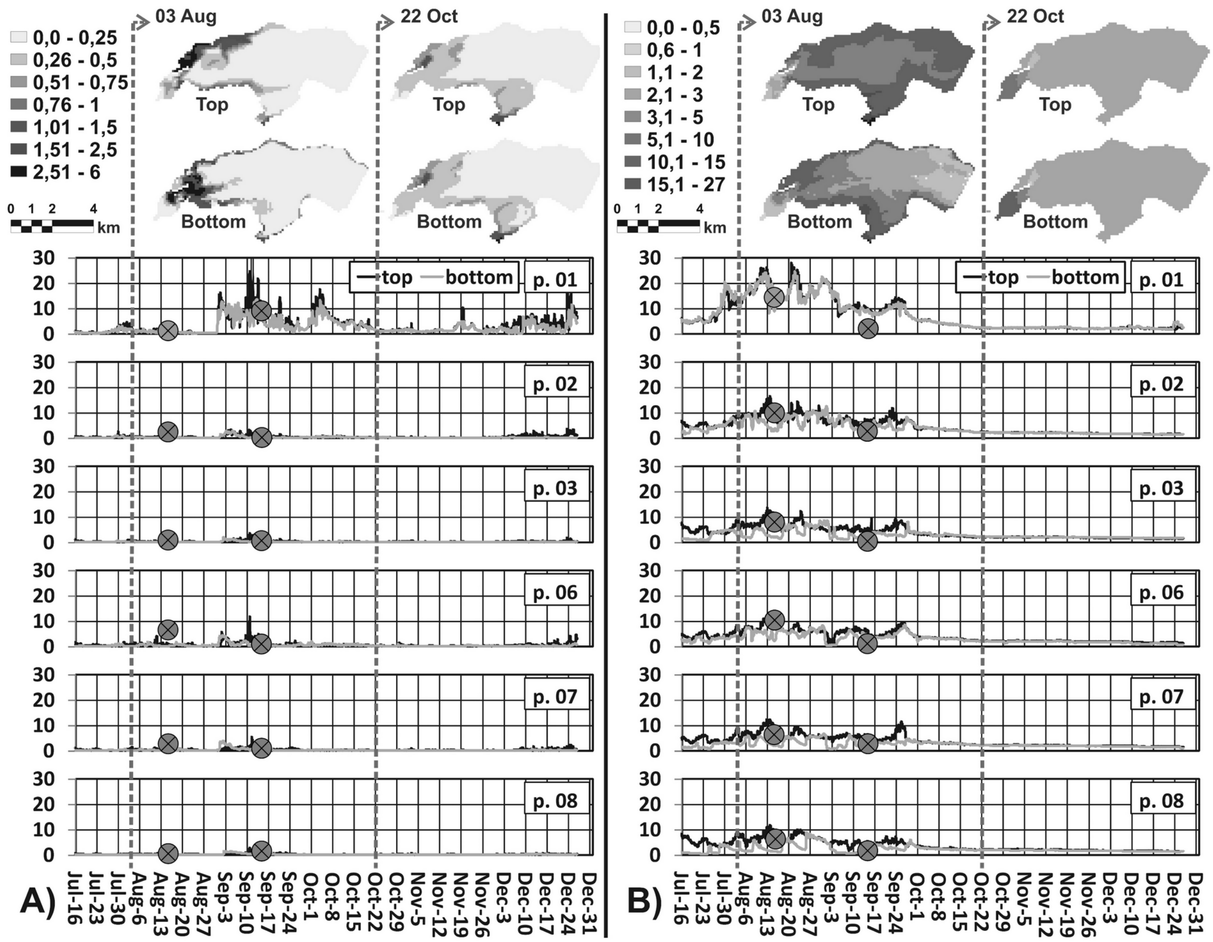

Fig. 8. Simulated changes in the abundance of FLAGE (A) and DIAT (B) phytoplankton groups at monitoring points (for point locations see Fig. 1) and spatial distribution of these groups on 3rd August and 22nd September 2010 (cross-marks represent observed data; dashed vertical lines represent two dates presented on the maps above line charts).

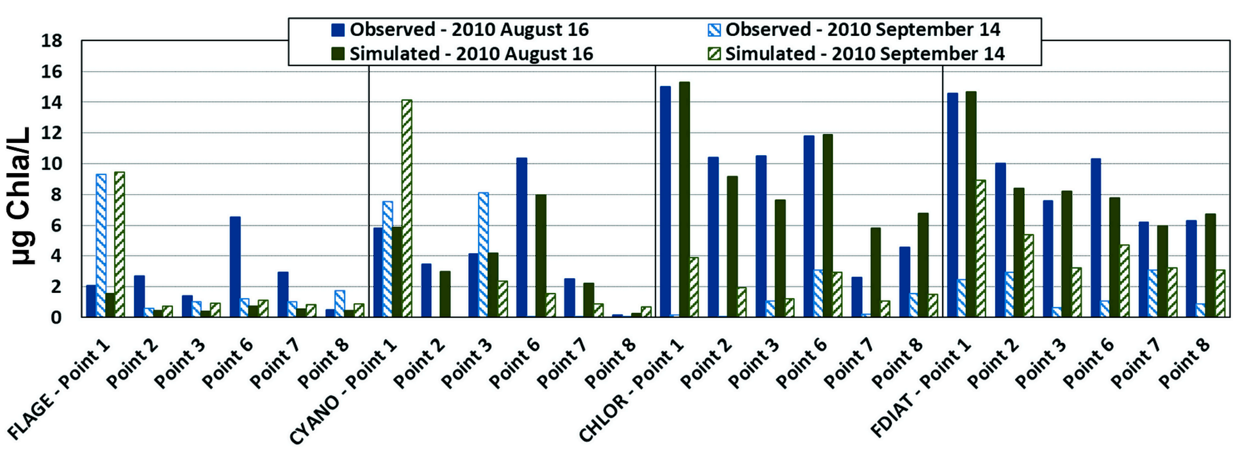

Fig. 9. Abundance of four phytoplankton groups observed and simulated at six monitoring points on 16th August and 14th September 2010.

common simplification reported by Kärcher et al., 2020) but was tested over all depths for which the temperature and chlorophyll *a* were simulated and observed (Ulańczyk et al., 2018). The impact of changes in the water temperature (induced by water mixing events) on chlorophyll *a* concentration was precisely reflected in the model. Such events may pose a risk of sudden water quality deterioration and are often reported (Zhang et al., 2019). The model presented in the study allowed accurate calculation not only of the concentration of phytoplankton but also the concentration of individual groups of phytoplankton. The concentration of phytoplankton groups varies in time and space, which would be difficult to observe based on the monitoring data only. These variations result from an even greater number of factors than in the case of chlorophyll *a* concentration, as each group of phytoplankton responds differently to the growth limiting factors. Lindenschmidt and Chorus (1998) reported changes in the concentration of phytoplankton groups calculated using a similar approach (DYRESM model) as a response to

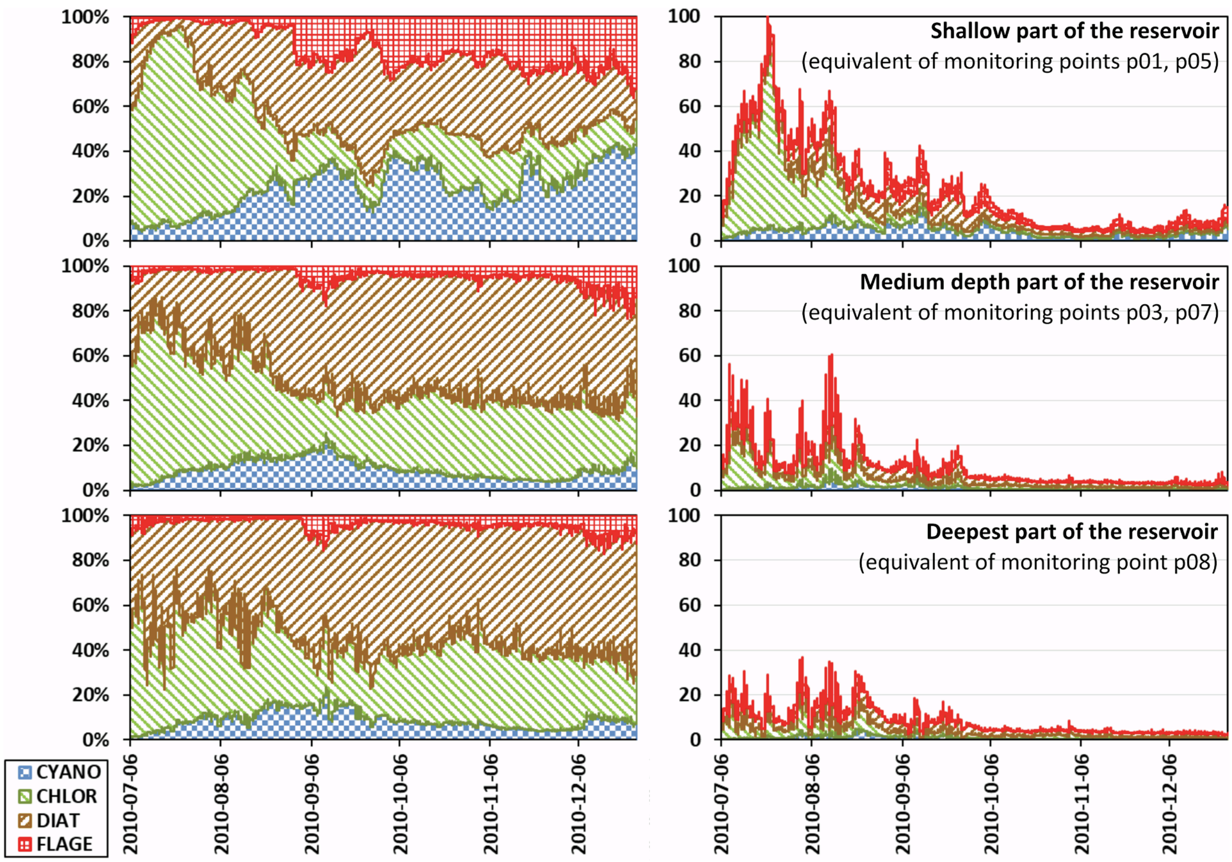

Fig. 10. Simulated concentration and share of four phytoplankton groups in the period July–December 2010 and in three areas of different depths.

water stability phases and nutrient availability. The general conclusions are in accordance with the results of the analysis presented in this paper, e.g. increased diatom concentration in well-mixed water, i.e. in fall and after short mixing events in summer in the case of Goczałkowice Reservoir. The increased concentration is not primarily a result of the increased availability of nutrients but a result of enhanced suspension of diatoms. In terms of other results, like greater phytoplankton diversity in periods of intermittent mixing, Goczałkowice Reservoir is also similar to Lake Tegel modeled by Lindenschmidt and Chorus (1998). After water mixing events, more diversified phytoplankton composition was estimated to occur near the surface and in the shallow parts of the reservoir, where mixing events were followed by a decrease in water temperature. Such a phenomenon was also reported by Schabhüttl et al. (2013) based on controlled laboratory experiments on various mixed communities of phytoplankton groups dominating in Goczałkowice Reservoir (i.e. CYANO, CHLOR and DIAT).

4.3. Application of outcomes

Similarly to other studies (Carraro et al., 2012; León et al., 2006; Missaghi and Hondzo, 2010; Romero et al., 2004; Yajima and Choi, 2013), this one confirms that, in spite of a large number of uncertainties, complex mathematical models can be successfully applied to simulate the concentrations of chlorophyll *a* and individual phytoplankton groups in reservoirs characterized by dynamically changing hydrometeorological conditions and nutrient availability.

With such tools, it is possible to provide detailed real-time information or forecasts regarding the concentrations of chlorophyll *a* and groups of phytoplankton. The presented model has already been used in a real-time mode, serving as a continuous information system similar to those reported by Mitreski et al. (2004) and Lang et al. (2010) presenting the archival and present concentration of chlorophyll *a* with its spatial distribution. In such systems, the simulated chlorophyll *a* concentration is used as an indicator of a lake's trophic status and as an early warning indicator of harmful algal blooms (Huang et al., 2012) and real-time control systems (Imberger et al., 2017; Marti and Imberger, 2015). The relatively good accuracy of the simulated phytoplankton concentrations in Goczałkowice Reservoir (described in Section 4.2) also allows use of the presented method to investigate long-term scenarios and to assess, for example, the combined impact of climate and land use change. In the case of Goczałkowice Reservoir, the applicability of the results can be confirmed by the report by Yoshioka and Yaegashi (2020) who analyzed the applicability of mathematical models for the prevention of algal bloom in a dam reservoir in Japan. The direct continuation of the work presented in this study had an implementation rather than research character. It included an application of the model of Goczałkowice Reservoir to simulate the impact of the discharge from fishponds located near to the Bajerka River outflow to the reservoir, and to assess the impact of dredging the reservoir near to the inflow of the Vistula River. The dredging was planned in order to restore the original geometry of the Vistula River channel which was blocked by sediments transported with surface waters. Not only was the study the basis for further analysis commissioned by the Goczałkowice dam operator, it was also the basis for similar studies dedicated to other dam reservoirs in the region, e.g. Rogoźnik I Reservoir, Paprocany Lake and Kozłowa Góra Reservoir, proving the transferability of the approach presented here (Absalon et al., 2020; www.interreg-central.eu/Content.Node/PROLINE-CE.html).

5. Conclusions

According to the model, verified with real data, both spatial and temporal changes in the chlorophyll *a* concentration are of significant magnitude. Such changes depend significantly on water stratification,

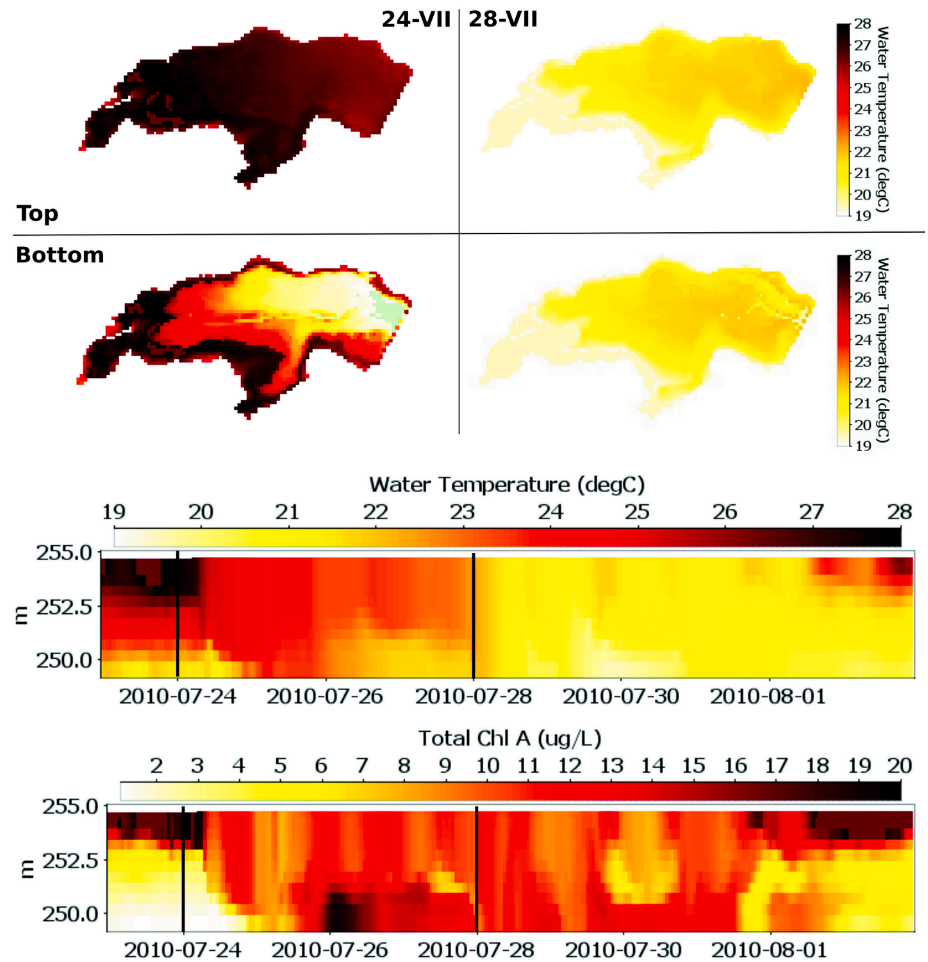

Fig. 11. Maps (upper part of the figure) present the water temperature in surface (top) and bottom water layers on two days: 24th and 28th July 2010, i.e. before and after one of the water mixing events. Two depth vs time charts present the simulated water temperature and chlorophyll *a* concentration in the deepest part of the reservoir (vertical black lines on charts represent two dates presented on the maps above).

jointly with seasonal water temperature distribution in the reservoir body, near the bank and in the backflow area as well as during water mixing events. Thus, changes in phytoplankton production in Goczałkowice Reservoir in a year with high flood are driven mainly by the water temperature and indirectly by water mixing. During summer mixing events lasting 4–5 days, the average difference between bottom and surface water temperature decreased from 4 to 10 °C to 0–1.5 °C. These events caused increases in the chlorophyll *a* concentration from 7 to 55–90 μg L^{-1}. Comparisons of simulated water temperature and both observed and simulated chlorophyll *a* concentration confirmed that these variables are significantly correlated. Correlation of hourly chlorophyll *a* concentration and water temperature was 0.70, ranging from 0.55 in the bottom water layer to 0.81 in the surface (1 m) water layer, while for daily outputs it was 0.74 ranging from 0.60 to 0.83. The correlation of changes in the vertical flow velocity and changes in the chlorophyll *a* concentration was also of great importance, because it indicates the impact of vertical flow (mixing of water layers) on the change in the chlorophyll *a* concentration. Such a correlation for 3-day changes in the chlorophyll *a* concentration was equal to 0.81, ranging from 0.66 to 0.89 in individual water layers (p-value less than 0.001). These relations were stronger than that of chlorophyll *a* to nutrient (N, P and Si) concentrations, which is not a general rule but a phenomenon reported for part of lakes and dam reservoirs worldwide.

While the simulated chlorophyll *a* concentration was well matched to hourly monitoring data (MSE = 5.6, NS = 0.51, $R = 0.72$ and p-value = 0.0007), model verification was also satisfactory regarding individual groups of plankton: most of the observed concentrations of individual phytoplankton groups differed from the simulation results by less than 25% and the model accurately reflected 74% of observed trends in concentrations.

The method used in this study allowed the assessment of a much more detailed spatial and temporal distribution of phytoplankton groups compared with conventional monitoring techniques. It was estimated that the phytoplankton community was dominated by Chlorophytes and Diatoms with a larger share of Chlorophytes in shallow parts of the reservoir. This domination was weaker after water mixing events in summer and especially after the fall turnover. The increase in phytoplankton diversity was estimated to occur mainly near the surface and in shallow parts of the reservoir.

The outcomes of the presented study in terms of the monitoring and modeling results were used in practice by the Goczałkowice dam operator to analyze the effects of management scenarios. Additionally, the approach related to the model parameterization and calibration was applied to other dam reservoirs in the region. Therefore, the presented work proves that dynamic modeling of phytoplankton concentration as a primary indicator and changes in water temperature and stability as supplementary indicators can be used in practice and supports the management and protection of multi-purpose reservoirs like Goczałkowice Reservoir.

CRediT authorship contribution statement

Rafał Ulańczyk: Conceptualization, Methodology, Formal analysis, Writing - original draft, Data curation. **Czesław Kliś:** Conceptualization, Methodology, Data curation, Writing - original draft. **Bartosz Łozowski:** Methodology, Writing - review & editing, Investigation, Software, Validation, Formal analysis. **Agnieszka Babczyńska:** Writing - review & editing, Validation. **Andrzej Woźnica:** Supervision, Validation, Investigation. **Jacek Długosz:** Data curation, Resources. **Elżbieta Wilk-Woźniak:** Writing - review & editing, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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